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ON THE INCIDENCE OF STRONG MG II ABSORBERS ALONG GRB SIGHTLINES

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ABSTRACT

We report on a survey for strong (rest equivalent width $W_r \geq 1$Å), intervening Mg II systems along the sightlines to long-duration gamma-ray bursts (GRBs). The GRB spectra which comprise the survey have a heterogeneous mix of resolution and wavelength coverage, but we implement a strict, uniform set of search criteria to derive a well-defined statistical sample. We identify 14 strong Mg II absorbers along 14 GRB sightlines (nearly every sightline exhibits at least one absorber) with spectra covering a total pathlength $\Delta z = 15.5$ at a mean redshift $\bar{z} = 1.1$. In contrast, the predicted incidence of such absorber systems along the same path length to quasar sightlines is only 3.8. The roughly four times higher incidence along GRB sightlines is inconsistent with a statistical fluctuation at greater than 99.9% c.l. Several effects could explain the result: (i) dust within the Mg II absorbers obscures faint quasars giving a lower observed incidence along quasar sightlines; (ii) the gas is intrinsic to the GRB event; (iii) the GRB are gravitationally lensed by these absorbers. We present strong arguments against the first two effects and also consider lensing to be an unlikely explanation. The results suggest that at least one of our fundamental assumptions underpinning extragalactic absorption line research is flawed.

Subject headings: gamma rays: bursts

1. INTRODUCTION

Shortly after the discovery of quasars (Schmidt 1963), researchers realized that one could study distant gas in the universe by analyzing absorption lines in the spectra of these distant objects (e.g. Bahcall & Salpeter 1965). Although debate persisted for many years as to whether the observed gas was intrinsic to the quasar or at cosmological distance, the latter view is now almost universally accepted and current research focuses on studying the dark matter power spectrum (e.g. Croft *et al.* 2002), the interstellar medium of high z galaxies (Wolfe, Gawiser & Prochaska 2005), metal enrichment (Schaye *et al.* 2003; Simcoe, Sargent & Rauch 2004), and reionization (White *et al.* 2003).

Upon establishing that long-duration ($t > 2$s) gamma-ray bursts (GRBs) are extragalactic (Metzger *et al.* 1997) with redshifts exceeding all but the most distant quasars (Kawai *et al.* 2006), researchers realized that one could use the transient, bright afterglows to perform similar observations as those for quasars (e.g. Vreeswijk, Møller & Fynbo 2003; Chen *et al.* 2005). Although the majority of analysis to date has focused on the gas associated with the GRB host galaxy (e.g. Mirabal *et al.* 2002; Savaglio, Fall & Fiore 2003), even the first GRB spectrum showed the presence of intervening gas at redshifts significantly lower than the highest redshift system (Metzger *et al.* 1997). The proposed applications include studying reionization at yet greater distance than QSOs and probing the Lyα forest on a well-behaved, power-law continuum (e.g. Lamb & Reichart 2000; Lazzati *et al.* 2001).

Here, we report the results from a survey of strong Mg II absorption systems. These systems were among the first intervening absorption lines discovered in quasar spectra because (i) the large rest wavelengths of the doublet allows for its detection in optical spectra for redshifts as small as 0.15; and (ii) the doublet has a large oscillator strength and is resolved with even low-resolution (FWHM ≈ 5Å) spectroscopy. As such, the Mg II absorbers were one of the first classes of quasar absorption line systems to be surveyed (Steidel & Sargent 1992). Follow-up observations have shown that these absorbers trace relatively bright galaxies (Lanzetta 1993; Ménard *et al.* 2005; Zibetti *et al.* 2005) and reside in dark matter halos with $M \approx 10^{12} M_\odot$ (Bouché, Murphy & Péroux 2004; Prochter *et al.* 2006).

In many of the GRB spectra acquired to date, the authors have reported the presence of a Mg II absorber with rest equivalent width $W_r > 1$Å. Jakobsson *et al.* (2004) noted that the galaxies identified with these absorbers may consistently occur at small impact parameter ($\rho \approx 10$kpc) from the GRB sightline. Over the past year, our collaboration (GRAASP[8]) has obtained moderate to high-resolution observations of afterglows for GRB discovered by the *Swift* satellite (Gehrels *et al.* 2004). In this Letter, we perform a search for strong ($W_r > 1$Å) Mg II absorbers along these GRB sightlines and those reported in the literature. We compare the results to our recent determination of the incidence of strong Mg II systems along the sightlines to quasars in the Sloan Digital Sky Survey (SDSS; Prochter, Prochaska & Burles 2006; Prochter *et al.* 2006).

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2. THE STRONG MG II STATISTICAL SAMPLE ALONG GRB SIGHTLINES

Owing to the transient nature of GRB afterglows, optical spectroscopy has been obtained at many observatories with a diverse set of instruments and instrumental configurations. This includes our own dataset (Prochaska *et al.* 2006a,b) which is comprised of observations acquired at the Las Campanas, Keck, Gemini, and Lick Observatories with the HIRES (Vogt *et al.* 1994), MIKE (Bernstein *et al.* 2003), GMOS (Hook *et al.* 2004) and Kast spectrometers, respectively. Nevertheless, a 1Å Mg II absorber is sufficiently easy to identify that one can establish a set of criteria that will yield a well-defined search path and statistical sample.

The criteria imposed are: (i) the data must be of sufficient quality to detect both members of the doublet at $> 3\sigma$ significance; (ii) the spectral resolution must resolve the doublet (we demand FWHM < 500 km s^{-1}); (iii) the search is limited to outside the Lyα forest. To provide a uniform comparison with low-resolution surveys, we group all individual Mg II components within 500 km s^{-1} of one another into a single system and measure the total equivalent width of the Mg II 2796Å transition. For each of our GRB spectra and those reported in the literature, we define a starting and ending redshift to search for Mg II absorbers, z_{start} and z_{end}. We define z_{start} as the *maximum* of: $1215.67(1 + z_{GRB})/2796$, 0.359 (to match z_{min} for our SDSS survey), and $\lambda^{SNR}_{min}/2796$, where λ^{SNR}_{min} is the lowest wavelength in the spectrum where $\sigma(W_r) < 0.3$Å. Similarly, we define the ending redshift to be the *minimum* of: 3000km s^{-1} within z_{GRB}, $\lambda^{SNR}_{max}/2803$, and 2 (to match the highest redshift with good statistics in the SDSS survey). We have been conservative in defining these quantities and in several cases have obtained the original spectra to verify the published results. Table 1 presents the value for each of the GRB sightlines in this survey.

We have then searched these sightlines for strong Mg II absorbers and measured the rest equivalent width of the Mg II 2796 transition. Figure 1 presents a gallery of Mg II profiles from our GRAASP collaboration. Details on these observations will be provided in future papers (Prochaska *et al.* 2006a,b). For the literature search, we rely on the reported equivalent width measurements. In nearly every case, the identification of the Mg II doublet is confirmed by the presence of strong Fe II absorption at shorter wavelengths. Table 1 lists the statistical sample. It is astonishing that nearly every GRB sightline exhibits a strong Mg II absorber and one of those without shows an absorber with W_r very nearly equal to 1Å (GRB 050730). Furthermore, we note that there are additional sightlines with insufficient spectral resolution and/or SNR to enter the statistical sample which have very strong Mg II absorbers ($W_r > 2$Å). Including these sightlines in the sample would only bolster the results discussed below.

3. RESULTS AND DISCUSSION

In Figure 2a we present the redshift path density $g(z)$ which describes the number of GRB sightlines available for a Mg II search as a function of redshift. This is a very small sample by quasar absorption line (QAL) standards. In Figure 2b, we show the cumulative number of Mg II absorbers detected along GRB sightlines (solid line) versus the number predicted by QSO statistics (dashed line). This curve was generated by convolving the $g(z)$ function for the GRB sightlines with the observed incidence of Mg II systems per unit redshift $\ell^{QSO}(z)$ from our survey of the SDSS (Prochter, Prochaska & Burles 2006; Prochter *et al.* 2006). Our updated analysis of Data Release 4 shows the incidence of strong Mg II absorbers per unit redshift $\ell^{QSO}(z)$ is well fitted by the following polynomial $\ell^{QSO}(z) = -0.026 + 0.374z - 0.145z^2 + 0.026z^3$ (Prochter *et al.* 2006). Note that these results are based on over 50,000 quasars and 7,000 Mg II systems with $W_r \geq 1$Å.

An inspection of the figure reveals that one observes a significantly higher incidence of strong Mg II absorbers toward the GRB sightlines than along the SDSS quasar sightlines. Assuming Poisson statistics, the observed incidence of 14 strong Mg II absorbers is inconsistent with the average value seen towards QSOs at $> 99.9\%$ significance. We have also assessed the significance of the observation by drawing 10000 sets of quasars from the SDSS-DR4 chosen to have a similar $g(z)$ function as the GRB sightlines. The results of this analysis is presented in Figure 3. We find an average of 3.8 strong Mg II absorbers, that less than 0.1% of the trials have over 10 systems, and that none has 14 absorbers. Therefore, it seems very unlikely that the difference in incidence between the GRB and QSO sightlines is only a statistical fluctuation. We note that GRB 060418, with three strong absorption systems, is a rare object. Monte-Carlo simulations reveal that only 2.6% of randomly chosen sets of 14 quasar lines-of-sight result in the inclusion of such a system. Removing this GRB from consideration, however, has the combined effect of removing both Mg II systems as well as a line-of-sight, which reduces $g(z)$, leaving little qualitative difference in the statistical result of our analysis.

As with any astronomical survey, there are a number of associated selection biases or possibly incorrect assumptions to the analysis. We identify three effects which could explain the results presented here: (i) dust in the Mg II absorbers has obscured faint quasars and led to a severe underestimate in $\ell^{QSO}(z)$; (ii) the majority of the strong Mg II absorbers along the GRB sightline are not cosmological but are intrinsic to the GRB event; (iii) GRB with bright, optical afterglows have been gravitationally lensed by foreground galaxies hosting strong Mg II absorbers. The first effect, a selection bias, has been discussed extensively for QAL absorbers (Ostriker & Heisler 1984; Fall & Pei 1993). Recently, York *et al.* (2006) have shown that Mg II absorbers do impose a non-zero reddening on its quasar spectrum, but that the average reddening for $W_r < 2$Å systems is $E(B-V) < 0.01$ mag. Therefore, we consider it very unlikely that obscuration bias is the dominant explanation.

Are the Mg II absorbers along GRB sightlines intrinsic to the GRB? Absorption systems intrinsic to the quasar environment have been identified at velocities Δv in excess of 50000 km s^{-1} (Jannuzi *et al.* 1996). These absorbers are identified because of very wide profiles, equivalent width variability, and/or evidence for partial covering in the doublet line-ratios (e.g. Barlow, Hamann & Sargent 1997). Although the strong Mg II absorbers show relatively wide absorption profiles (by default) for QAL systems, the velocity widths are less than several hun-

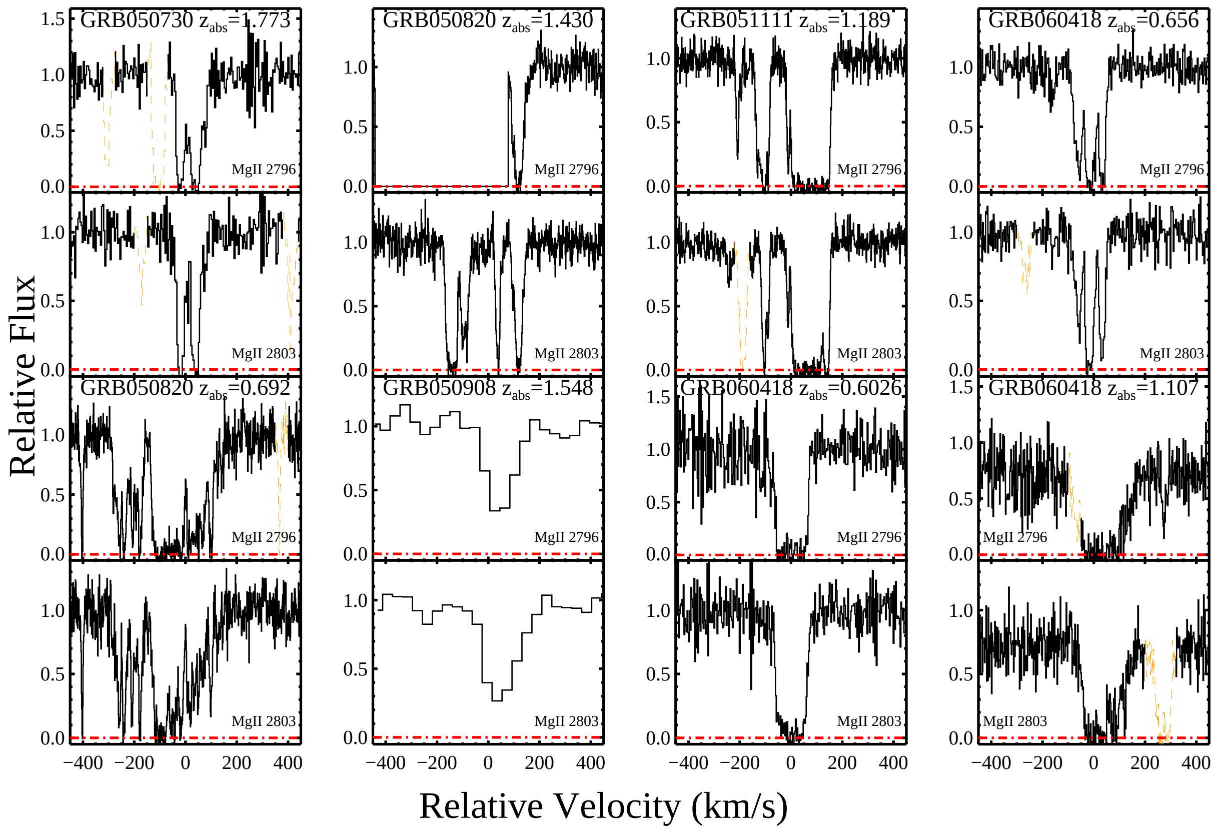

FIG. 1.— Velocity profiles of eight of the Mg II absorbers identified along the sightlines to GRB by our GRAASP collaboration. See Prochaska *et al.* (2006a) and Prochaska *et al.* (2006b) for details of the observations. Dashed lines indicate features from coincident transitions.

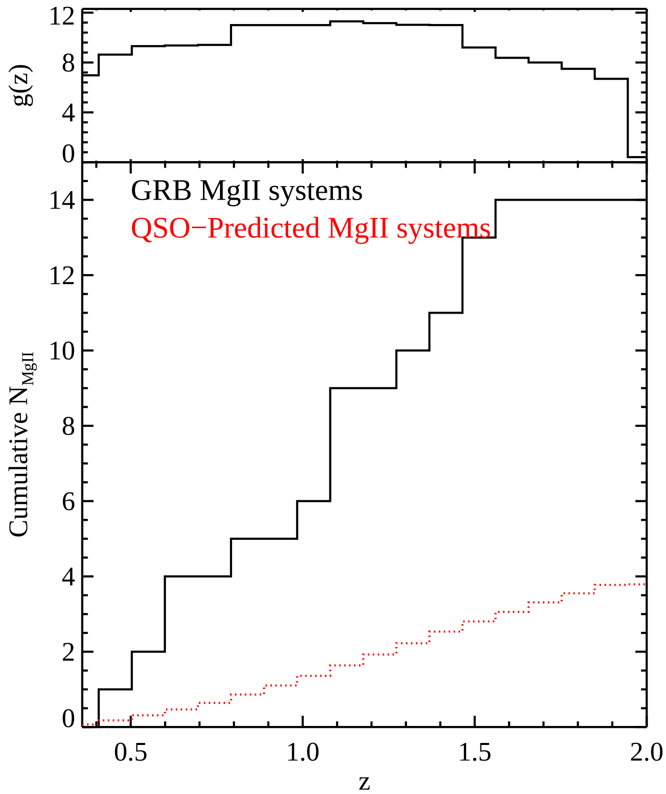

FIG. 2.— Upper panel: The redshift path density $g(z)$ for the 14 sightlines which have sufficient SNR and spectral resolution to be included in the statistical sample. Lower panel: Cumulative number of Mg II systems identified along the GRB sightlines (black curve). The red curve shows the predicted number of systems adopting the incidence of Mg II systems $\ell^{QSO}(z)$ measured along QSO sightlines (Prochter *et al.* 2006). The incidences observed for GRB and QSO sightlines are inconsistent at the greater than 99.9% level.

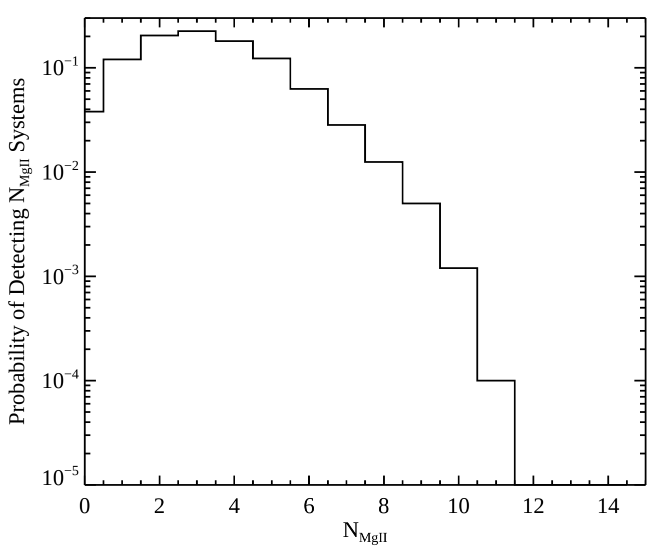

FIG. 3.— Probability of detecting $N_{\rm MgII}$ strong Mg II systems calculated from a set of 10000 trials where we randomly drew quasars from the SDSS dataset constrained to have nearly the same $g(z)$ distribution as the GRB sightlines.

dred km s^{-1} , i.e., much less than the implied relativistic speeds (Table 1). The gas is generally highly ionized, although there are also examples of low-ionization states. An excellent way to test for the cosmological nature of the Mg II absorbers along GRB sightlines is to search for the host galaxies. Indeed, several authors have reported the identification of the host galaxies for strong, intervening Mg II systems along GRB sightlines (Masetti *et al.* 2003; Vreeswijk, Møller & Fynbo 2003; Jakobsson *et al.* 2004). Only a small fraction of the strong Mg II systems listed in Table 1 have been identified, however, and an intrinsic origin for individual members of the sample is not entirely ruled out. Nevertheless, we consider it an improbable explanation at the current time.

Are the galaxies hosting the strong Mg II absorbers lensing the background GRB events? There are several lines of evidence in support of this conclusion. First, the strong Mg II absorbers reside in relatively massive dark matter halos $M \approx 10^{12} M_\odot$ (Bouché, Murphy & Péroux 2004; Prochter *et al.* 2006). Second, the survey is biased to GRB with bright optical afterglows, i.e. we are selecting a subset of the GRB population. Third, nearly every GRB sightline shows a $W_r > 0.5$ Å Mg II system. Fourth, the impact parameter for several of the foreground galaxies is small (Jakobsson *et al.* 2004). Fifth, the luminosities of low redshift ($z < 0.5$) GRBs appear to be significantly lower than those of the high z events. None of these arguments, however, is particularly strong.

Furthermore, there are a number of arguments against strong lensing. First, estimates for the lensing rate based on the photon number fluxes predict a small lensing rate (Porciani & Madau 2001). Second, one does not always identify a bright foreground galaxy at small impact parameter ($< 1''$) from the GRB sightline. We note that lensing would deflect the sightline, perhaps by more than 10 kpc, but that for the redshifts of interest here this translates to $\sim 1.3''$. Third, it is unlikely that galaxy or cluster lensing would provide sufficiently large magnification to explain the very bright afterglows. Finally, there have been no reports of multiple images in late time optical follow-up observations. For these reasons, we consider strong lensing to be an unlikely explanation.

Frank *et al.* (2006) have considered an alternative explanation for the observed effect, namely that the difference in sizes between GRBs and QSOs leads to lower equivalent widths in QSO sightlines. We believe, however, that this model is ruled out because one does not observe unsaturated Mg II lines (at high resolution) where the doublet is not in a 2 : 1 ratio (Churchill 1997).

In summary, we have reported on a statistically significant difference in the incidence of strong Mg II absorbers between GRB and QSO sightlines. Although it is partly an a-posteriori result, the result has the predictive test that a larger sample of GRB sightlines will continue to show an excess of systems in comparison with quasar sightlines. At present, we have not identified a satisfactory single explanation for this phenomenon. Our results suggest that at least one of our fundamental assumptions underpinning extragalactic absorption line research is flawed. Before concluding, we wish to note that Stocke & Rector (1997) reported a similar enhancement in the incidence of Mg II systems along the sightlines to BL Lac objects, quasar-like

phenomenon with spectra similar to GRB that are also believed to be relativistically beamed jets. It may be worth considering their result in greater detail.

The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. We thank P. Madau for helpful conversations. We acknowledge the efforts of S. Vogt, G. Marcy, J. Wright and K. Hurley in obtaining the observations of GRB 050820. GEP and JXP are supported by NSF grant AST-0307408. JXP, H-WC, and JSB are partially supported by NASA/Swift grant NNG05GF55G.

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Table 1
Survey Data for Mg II Absorbers Along GRB Sightlines

GRB	z_{GRB}	z_{start}	z_{end}	z_{abs}	W_r(2796 Å)	Δv (km s^{-1})	Reference
$W_r(2796) \geq 1$ Å Mg II Statistical Sample							
000926	2.038	0.616	2.0				8
010222	1.477	0.430	1.452	0.927	1.00 ± 0.14	74,000	1
				1.156	2.49 ± 0.08	41,000	
011211	2.142	0.359	2.0				2
020405	0.695	0.359	0.678	0.472	1.1 ± 0.3	65,000	11
020813	1.255	0.359	1.232	1.224	1.67 ± 0.02	4,000	3
021004	2.328	0.359	2.0	1.380	1.81 ± 0.37	97,000	4
				1.602	1.53 ± 0.37	72,000	
030226	1.986	0.359	1.956				5
030323	3.372	0.824	1.646				7
050505	4.275	1.414	2.0	1.695	1.98	176,000	6
050730	3.97	1.194	2.0				
050820	2.6147	0.359	1.850	0.692	2.877 ± 0.021	192,000	
				1.430	1.222 ± 0.036	113,000	
050908	3.35	0.814	2.0	1.548	1.336 ± 0.107	147,000	
051111	1.55	0.488	1.524	1.190	1.599 ± 0.007	45,000	
060418	1.49	0.359	1.465	0.603	1.251 ± 0.019	124,000	
				0.656	1.036 ± 0.012	116,000	
				1.107	1.876 ± 0.023	50,000	
Other Mg II Systems Reported/Detected Along GRB Sightlines							
970508	0.835			0.767	0.736 ± 0.3	17,000	7
991216	1.022			0.770	2.0 ± 0.8	40,000	2
				0.803	3.0 ± 0.7	34,000	
011211				0.316	2.625 ± 1.418	210,000	
030226				1.042	0.9 ± 0.1	109,000	
				1.963	5.0 ± 0.2	2,000	
030328	1.522	0.359	1.497	1.295	0.42	28,000	12
030429	2.66			0.8418	3.3 ± 0.4	179,000	9
050505				2.265	1.74	134,000	
050730				1.773	0.922 ± 0.019	157,000	
				2.253	0.540 ± 0.017	120,000	
050820				0.483	0.505 ± 0.023	213,000	
050908				2.153	0.89 ± 0.100	93,000	
060206	4.048	1.206	1.529	1.480		179,000	10

References. — 1: Mirabal *et al.* (2002) 2: Vreeswijk *et al.* (2006) 3: Barth *et al.* (2003) 4: Mirabal *et al.* (2003) 5: Klose *et al.* (2004) 6: Berger *et al.* (2005) 7: Metzger *et al.* (1997) 8: Castro *et al.* (2003) 9: Jakobsson *et al.* (2004) 10: Fynbo *et al.* (2006) 11: Masetti *et al.* (2003) 12: Maiorano *et al.* (2006)